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DEVELOP SILICONE ENCAPSULATION SYSTEMS FOR TERRESTRIAL SILICON SOLAR ARRAYS

Final Report

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Dow Corning Corporation
Midland, Michigan

U.S. Department of Energy

Solar Energy

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FINAL REPORT

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The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

by

DOW CORNING CORPORATION
Midland, Michigan 48640

December, 1979

ABSTRACT

This work resulted in two basic accomplishments. The first was the identification of DOW CORNING® Q1-2577 as a suitable encapsulant material for use in cost effective encapsulation systems. The second was the preparation of a silicone-acrylic cover material containing a durable ultraviolet screening agent for the protection of photo-oxidatively sensitive polymers.

The most cost effective method of encapsulating photovoltaic modules is the one which requires the fewest and least complicated steps and which uses a minimum amount of material.

The most expeditious method of fabrication is one in which the encapsulant material performs the combined function of adhesive, pottant, and outer cover. The costs of the encapsulant can be minimized by using it as a thin conformal coating.

Our evaluation of methods by which to process encapsulation systems and the screening of candidate materials took those factors into consideration.

One encapsulation system using silicones was identified from this work which provided protection to photovoltaic cells and survived the JPL qualification tests.

This encapsulation system uses DOW CORNING® Q1-2577, a conformal coating from Dow Corning as the combined adhesive, pottant and cover material. The lowest cost encapsulation system using Q1-2577 had Super Dorlux® as the substrate structural member. The overall material cost of this encapsulation system is 0.74¢/ft² (1980 dollars) based on current material prices, which could decrease with increased production of Q1-2577.

Subsequent to identifying the best silicone encapsulation system, a silicone acrylic cover material containing a durable ultraviolet screening agent was prepared and its effectiveness in protecting photo-oxidatively sensitive polymers was demonstrated.

SUMMARY AND RESULTS

Technology Review

Silicone resins and elastomers have been used successfully for the protection of electrical devices and electronic circuitry for over 30 years. They are well suited for this application because the polymers are free of ionic contaminants and consequently have good resistivity, high dielectric strength and a low dissipation factor. These properties are also required for the protection of photovoltaic cells.

Although silicones have high water vapor transmission rates, the amount of water they can absorb is low and they retain good physical, chemical and electrical properties when saturated with water vapor. Good adhesion of the silicone material to the electrical device is necessary to provide corrosion protection in high humidity environments.

Silicone elastomers have been used as sealants in weathering environments for many years and make the construction of free standing glass walls possible. These sealants retain most of their elasticity and strength after 20 years outdoor exposure. Silicone resins are used in silicone-organic paint formulations, and the durability and gloss retention of this pigmented system can be correlated to the fraction of silicone resin used.

A review of the experience of the photovoltaic industry in using silicone materials as encapsulants disclosed the following:

1) Virtually all of the experience in commercial applications was with elastomeric silicone products such as SYLGARD® 184 and GE 615 or gel consistency products such as DOW CORNING® Q3-6527.

2) These silicone products provide adequate protection if: a) a hard cover such as DOW CORNING® R4-3117 or Q1-2577 is used with the elastomeric encapsulants or b) the Q3-6527 gel is covered with glass or placed in a plastic film bag.

3) The use of elastomeric silicone encapsulants without a hard surface cover leads to a reduction in power output due to dirt pick-up.

4) Elastomeric silicone encapsulants delaminate from metal or glass substrates unless primers are used and care is taken during the fabrication of modules. The proper handling and use of these materials as well as the recommended primers can be found in the manufacturer's product information sheets.

5) Attempts to use high modulus silicone resins such as R4-3117, as thick coatings in direct contact with solar cells failed because of cell and encapsulant cracking caused by differences in thermal expansion.

The general view of the photovoltaic industry is that an improved, lower cost encapsulation system is required to achieve the 1986 DOE volume and price goals of 500 peak megawatts at $0.50 per peak watt. The encapsulation system must be amenable to automated large scale production.

This review of relevant technology provided abundant support for the investigation of silicone materials as cost effective encapsulants of photovoltaic materials.

Screening and Processing of Silicone Encapsulation Systems

The silicone materials were screened for use as cost effective encapsulants based on their physical properties, availability, and cost. Ease of processing, simplicity of design and cost of fabrication were the criteria used to assess the encapsulation designs. The following silicone based materials were identified as possible candidates for silicone based encapsulation systems:

DOW CORNING® Q1-2577 Conformal Coating - A clear silicone resin with good dielectric properties which cures to a tough dirt resistant polymer.

DOW CORNING® 808 Resin - A clear silicone resin higher in modulus than Q1-2577.

Blends of DOW CORNING® 840 Resin with acrylic resins such as B48N from Rohm and Haas - The purpose of using silicone-acrylic polymer blends is to reduce material cost without an unacceptable decrease in durability.

DOW CORNING® 3140 RTV - A clear, compliant elastomer proposed as an encapsulant.

SYLGARD® 184 - Another clear silicone elastomer proposed for use as an encapsulant. This material provides a good reference point based on extensive experience by the photovoltaic industry in using this product.

DOW CORNING® X1-2561 Solventless Resin - An experimental resin proposed for use as a conformal coating.

DOW CORNING® 96-083 Adhesive - A clear silicone adhesive.

DOW CORNING® Z-6082, Z-6030, Z-6020, 1204 Primer - Organofunctional silanes proposed as primers to provide adhesion of the coatings to substrates.

The materials of construction identified as candidates to provide mechanical support were:

<u>Super</u> <u>Dorlux®</u> - An outdoor weathering grade of hardboard from Masonite Corporation. Proposed for use as a substrate support material.

<u>Solatex®</u> - A clear, low iron containing glass from ASG Industries proposed a a superstrate support material.

Metals such as steel and aluminum were considered as substrate materials, however, no system could be envisioned which would be cost effective when the cost of the metal and cost of electrical isolation of the cell-string were combined.

The two encapsulation concepts generated consisted of: a) a transparent superstrate with solar cells adhesively bonded with a thin glue line, coated with a white pigmented conformal coating and b) a solid substrate such as Super Dorlux® painted white with cells bonded to the surface and overcoated with a thin clear conformal coating.

Spectrolab supplied the cell circuits used in this evaluation which were two inch diameter 2-cell circuit-strings using silver-ink screened metallization with solder-plated copper ribbon interconnectors.

Assessment of Encapsulation Concepts

Several tests were used to assess the relative merit of the encapsulation concepts which had been generated.

The measurements of material properties which were obtained to determine their suitability for use as adhesives, pottants or outer cover were:

1) Initial Tangential Moduli
2) Glass Transition Temperature

Also, all information on the candidate materials which was available through data sheets or in-house testing was used in assessing the relative performance of the materials.

The stress and exposure tests which were used to assess the candidate concepts were:

1) Exposure to UV radiation using an Atlas Filtered Weather-Ometer®.
2) Accelerated dirt pick-up using carbon black powder.
3) Natural outdoor exposure and its effect on the performance of cells coated with candidate materials.

The initial tangential moduli were used to estimate the stress relieving characteristics of the candidate materials and during the evaluation of encapsulation concepts a good correlation was found between materials having high tangential modulus and the tendency of these materials to crack during thermal cycling.

This tendency to crack during thermal cycling also correlated well with sharp glass transitions of materials which occurred within this temperature range.

All of the candidate encapsulation materials resisted degradation during exposure to UV radiation. The silicone resins having high phenyl content were harmed by UV more than those with low or insignificant amounts of phenyl. After 4,000-5,000 hours exposure, these resins with high phenyl content had significant loss of surface gloss and developed small cracks and checks while those with low or insignificant phenyl content did not visibly change. This period of exposure in the Weather-Ometer® corresponds to years of equivalent UV radiation from outdoor exposure. The samples which were made by coating Super Dorlux® particle board with the candidate silicone coatings and then exposed in the Filtered Weather-Ometer® degraded and delaminated along the edges which were uncoated but portions of the edge which were coated with silicone resin remained in good condition after 500 hours exposure demonstrating the protective properties of the silicone resins.

The accelerated dirt pick-up test did not correlate well with long term outdoor exposure. The long term outdoor exposure tests were more relevant and indicated that there is a significant loss in cell output for all of the materials tested. RTV 3140, a very soft silicone elastomer, became very soiled and had the greatest loss of power. There did not appear to be a good correlation between modulus of the resin and loss of cell power due to soiling for the other silicone based materials.

Evaluation of Candidate Encapsulation Concepts

The encapsulation concepts were evaluated by stressing two-cell modules made with the candidate silicone based materials using both the Super Dorlux® substrate and glass superstrate design.

The stresses were:

1) Thermal cycling from 25°C to 40.5°C at 95% relative humidity

2) Fifty days exposure at 70°C and 95% relative humidity

3) Thermal cycling from -40°C to +90°C.

All of the modulus came through the humidity stresses with negligible losses in power output and little evidence of corrosion.

The thermal cycling test (from -40°C to +90°C), however, caused all of the candidate conformal coatings except Q1-2577 to crack and check.

DOW CORNING® Q1-2577 was the only silicone based material which was both dirt resistant and compliant enough to pass the JPL Thermal Cycling Stress. This silicone conformal coating was used to prepare five 24-cell circuit string modules using Super Dorlux as the substrate and four 24-cell circuit string modules using glass as the superstrate. These modules were made in compliance with JPL's mini-module size requirements and were submitted to JPL for testing and evaluation.

The recently revised allocation of $1.40/ft^2 (1980 dollars) for the Encapsulation Task of the LSA Project includes the cost of framing. The material costs for the lowest cost encapsulation system using Q1-2577 and Super Dorlux® are less than this targeted amount. The minimum materials cost for this module design is estimated to be $.74/ft^2 (1980 dollars).

Silicone-Acrylic Cover Material

Subsequent to identifying the lowest cost silicone encapsulation system, work was initiated to demonstrate the feasibility of fabricating a silicone-acrylic cover material containing a non-fugitive UV screening agent. This work was successful and a cover film containing Permasorb MA was prepared in usable form. This film protects polymers which are sensitive to UV radiation.

Work is needed to optimize the formulation and determine the scope and limits of this technology.

All of the data and information on preparing and using this polymer was delivered to Springborn Laboratories under JPL supervision.

Springborn Laboratories will continue to investigate this technique of protecting UV sensitive polymers.

RESULTS AND DISCUSSION

Technology Review

The protection of photovoltaic cells requires a material which is durable, will prevent corrosion of metallization and interconnectors, and remain transparent.

A review of the information available on the long term weathering of silicones concerned with these performance criteria produced relatively few, well documented examples.

Although silicones have been used in outdoor applications and are known for their durability and performance in harsh environments, most of the applications in which they are used do not require the combination of corrosion protection and optical clarity.

Silicone elastomers are commonly used in outdoor weathering environments as sealants and roof coatings and have demonstrated excellent durability when used in these applications. Silicone resins provide increased life and durability to outdoor coatings and paints. These applications normally use silicone resins blended or coreacted with organic coating resins in pigmented formulations. The number of examples of clear coatings is quite limited.

Silicones have also been used for many years to provide protection to electrical components and electronic devices exposed to harsh humid environments. These silicone polymers have high rates of water vapor transmission, and therefore, an explanation for reconciling the good performance of these materials with their physical properties.

Protection of a surface depends on the quality and stability of the adhesive bond between the surface and the protective coating.

Malcolm White of Bell Labs[1,2] has proposed that silicone provide protection by chemically bonding substrate through silanol interaction and demonstrated that silicones do not allow liquid water to accumulate at the interface of a silicone encapsulated integrated circuit. Sailer and Kennedy[3] have reported similar findings:

> Initially, the choice of silicone-resin conformal coating and a silicone-rubber back-seal for an application where environmental protection is required may not seem prudent. It is well known that the permeability of these materials to most gases including water vapor is quite high; it is higher than many other plastics. The advantage of these materials is not in low transmission rate of moisture, but rather in their low moisture absorption and good chemical and electrical stability while "saturated".
>
> Surfaces coated with silicones have a hydrophobic character which prevents moisture from condensing and creating leakage paths. The low moisture absorption rate of silicones maintains the dielectric strength on coated surfaces and prevents electrical degradation. In short, the use of permeable silicone materials for encapsulation provides a package which "breathes" moisture in and out while attenuating the moisture to non-critical levels.

Sierawski[4], and Sierawski and Currin[5] have shown that the silicone elastomers with the appropriate chemical coupling primer can give corrosion protection in high humidity environments for automotive and solar applications. They have also reported that the silicone gels give corrosion protection and stress relief for the protection of delicate electronic components.

Kookootsedes and Lockhart[6] have shown that highly filled silicone encapsulants can also give excellent protection to electronic devices even at elevated temperatures. Performance after stressing of silicone encapsulated electronic devices and electrical equipment has also been demonstrated by

Jaffe[7], and VanWert and Ruth[8]. In both cases, retention of performance and physical properties was shown after thermal cycling and high humidity/temperature stressing. Jaffe also reported good cure under the leads of an electronic device using a silicone RTV.

The processing of silicone polymers removes ionic, corrosive contaminants and silicone materials are known for their inertness and cleanness. The catalyst chosen for crosslinking and curing these silicone materials for encapsulating photovoltaic cells must also be non-corrosive.

The requirements for the protection of photovoltaic cells are similar to those needed for the protection of these electronic devices. In addition to providing corrosion protection and stress relief for the interconnects, the photovoltaic application has the additional requirements of optical clarity and durability in a weathering environment.

Silicone resins have been used for many years by the coatings industry to up-grade the performance of durable exterior coatings. Brown reports that substituent groups on silicones can yield different properties in a silicone resin[9]. The organic substituents present in silicone polymers result from the organic groups contained in the silane monomers used to make the polymers. Phenyl and methyl are two common organic moieties on the silane monomers used to make silicone polymers.

Properties yielded by high methyl content:

Flexibility	Water Repellency
Low Weight Loss	Low Temperature Flexibility
Chemical Resistance	Fast Cure Rate
Arc Resistance	Gloss Retention
Heat Shock Resistance	U.V. & I.R. Stability

Properties yielded by high phenyl content:

Heat Stability	Oxidation Resistance
Thermoplasticity	Retention of Flexibility on Heat Aging
Toughness	Air-Drying

The improved durability a silicone resin can impart to a coating was shown by comparison of 30% and 100% silicone coatings with organic alkyds. The all silicone lost 4% of its initial 94% gloss after 36 months in Florida. An air drying silicone-alkyd lost 30% of its initial 85% gloss. The air drying organic-alkyd lost 90% of its initial 85% gloss[9]. After testing silicone-polyesters, it was found that for identical paint formulations except for silicone content, the formulation with more silicone retained its properties of gloss, non-chalking and non-checking better than that with less or no silicone. Thomas showed similar findings in tests with long oil soya alkyd coatings weathered in Midland, Michigan, and baked alkyds weathered in Florida[10]. In both cases, more silicone gave better performance as rated by retention of gloss.

Finzel has found not only do silicone-organic durable coatings weather better in the Dew Cycle Weather-Ometer® and Florida, but also that each resin system gives its own correlation of WOM effects of stressing to Florida effects of stressing[11].

A. Adhesion

One further area investigated in this technology review was the use of chemically coupling primers and chemicals to promote adhesion between dissimilar surfaces. It has been known for at least fifteen years now that organofunctional silanes can chemically react with organic resins, by proper choice of organo-reactive group of the silane, and metal or oxide surfaces through silanols formed on the silane after hydrolysis. Plueddemann has demonstrated the use of organo-silanes to adhere resin to glass in spite of the presence of water and differences in coefficient of thermal expansion (CTE)[12,13]. The use of a silane coupling agent in a plastic composite can cause a 100% increase in physical properties such as tensile, flexural and compressive strengths after exposure to moisure.

Two patents were also found describing the use of organoborates and alkyl or alkoxy titanates for bonding silicones to substrates[14,15]. These substrates include metal and siliceous materials such as glass. Liles reported successful bonding of a silicone molding compound to metal using an organosilicone hydride[16].

Since good adhesion of the silicone to a substrate is important, state-of-the-art primer technology was utilized in this study.

The performance of silicone materials used in outdoor applications or exposed outdoors for test purposes was reviewed. Data on clear silicone coatings having this kind of exposure was limited. The only examples of clear silicone materials were silicone resins coated on metal panels and one example of a silicone resin on glass cloth. Silicone resin materials usually contain significant amounts of aromatic components and because of this they can absorb UV radiation which leads to degradation. Silicone elastomers on the otherhand usually have little or no aromatic content.

Silicone materials with known weathering characteristics were exposed in an Atlas Filtered Weather-Ometer® to ascertain if this accelerated stress test could be correlated with outdoor exposure.

A direct correlation of the effects of time of exposure in the Weather-Ometer® to outdoor exposure could not be made due to the few number of samples and the variety of test sites. See Table I.

Two important and relevant results were obtained during this experiment:

1) Exposure for 3,000-4,200 hours in the Weather-Ometer® caused more damage to all of the resin coatings than 13 years outdoor exposure.
2) None of the silicone elastomers were visibly changed after 5,000-6,000 hours of exposure.

The checking and loss of gloss which occurred with the silicone resins could be attributed to their aromatic content.

Unfortunately, the silicone elastomers for which historical weathering data were available were pigmented and opaque, and therefore, their resistance to UV radiation could well be due to the lack of penetration by the UV light.

However, as part of this work we included examples of clear silicone elastomers which are currently commercially available and recommend for use outdoors. Three clear silicone elastomers; Clear Silicone Elastomer, RTV 3140 and SYLGARD® 184 were exposed in the Atlas Weather-Ometer® for more than 8,000 hours without any change in appearance.

B. Photovoltaic Industry Experience with Silicone Encapsulation Materials

The photovoltaic industry widely uses silicone elastomers as encapsulants for the protection of cells. The silicone material most widely used in photovoltaic applications are Dow Corning SYLGARD® 184 Resin and G.E. 615. Silicone elastomers were selected for this use because they are optically clear, they remain flexible in weathering environments, they are compatible with cell circuitry and they provide protection to these electronic devices in humid environments.

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The current encapsulation material cost of approximately $\$1/ft^2$ equates to \$0.10/watt. This value represents a signficant portion of the 1986 LSA cost goal of \$0.70/watt (in 1980 dollars).

This 1986 cost goal can only be achieved by using encapsulation materials in the most cost effective manner and by improving the methods used to manufacture modules.

Although the photovoltaic industry has been using silicone elastomers as the encapsulant for many years, some manufacturers have experienced problems using this type of elastomeric silicone material. The two principal reasons for the failures and dissatisfaction which some photovoltaic array manufacturers have experienced with silicone elastomer encapsulants have been due to:

1) Delamination of the encapsulant from the substrate.

2) Dirt pick-up and retention by soft elastomeric encapsulants with exposed surfaces.

The most common mode of failure of modules encapsulated with SYLGARD® 184 which occurred during the early stages of terrestrial photovoltaic commercialization was delamination of the encapsulant from the substrate. These results were obtained during JPL's Block I procurement of state-of-the-art modules and were widely publicized[17].

During the Block II procurement program, the use of adhesion promoters and more careful fabrication techniques reduced the number of modules which failed because of delamination.

Another factor which must be considered when silicone elastomers are used as encapsulants without a hard transparent cover is the relatively soft surface which is difficult to clean. The impact of this soil retention on module performance has not been completely resolved; however, a decrease in power output from modules exposed in urban areas such as New York City is greater than the power loss of modules exposed in rural areas.

A rather detailed analysis of silicone elastomer encapsulated modules was made by Spectrolab[18]. They felt that silicone materials were not practical encapsulants for a variety of reasons. Although a number of delaminations have occurred and decreases in power output due to soiling were observed in exposure studies conducted by MIT-Lincoln Laboratory[19], it is noteworthy that of 3,400 modules deployed a various sites for periods of up to 16 months, only 22 have failed. This is an outstanding performance record.

To date, no cleaning techniques has been identified which will recover all of the losses in power output due to soiling.

One array manufacturer has improved the cleanability and lowered dirt retention characteristics of silicone encapsulated modules by overcoating the elastomeric silicone encapsulant with a thin coating of a harder silicone resin[20].

One attempt to reduce the dirt pick-up was to use a high modulus silicone resin as the encasulant itself. Modules fabricated by Spectrolab using DOW CORNING® R4-3117 Conformal Coating, a higher modulus silicone resin, had much improved resistance to dirt pick-up; however, the higher modulus silicone resin as an encapsulant cracked during thermal cycling and during outdoor exposure studies[21]. A detailed analysis by JPL on the resin itself provided a rational explanation for this failure mode[22]. The strain created during thermal expansion due to a relatively high coefficient of thermal expansion caused enough tension stress to fracture the resin.

Generation of Methods for Screening and Processing Silicone Encapsulation Systems

The most cost effective method of encapsulating photovoltaic module is the one which requires the fewest and least complicated process steps and which uses a minimum amount of material.

The most expeditious method of fabrication is one in which the encapsulant material performs the combined function of adhesive, pottant, and outer cover. The costs of the encapsulant can be minimized by using it as a thin conformal coating.

Our evaluation of methods by which to process encapsulation systems and the screening of candidate materials took those factors into consideration.

The following silicone based materials were identified as possible candidates for silicone based encapsulation systems:

DOW CORNING® Q1-2577 Conformal Coating - A clear silicone resin with good dielectric properties which cures to a tough dirt resistant polymer. Proposed as a clear protective conformal coating and as a cover material for use with ultraviolet (UV) absorbers.

DOW CORNING® 808 Resin - A clear silicone resin used as a conformal coating and as a cover material for use with UV absorbers. This resin is a higher modulus resin than Q1-2577.

Blends of DOW CORNING® 840 Resin with acrylic resins such as B48N from Rohm and Haas - These combinations are proposed as clear conformal coatings and as UV screening cover materials. The purpose of using silicone-acrylic polymer blends is to reduce material cost without an unacceptable decrease in durability.

DOW CORNING® 3140 RTV - A clear, compliant elastomer proposed as an encapsulant. This concept would require an inexpensive dirt resistant cover.

SYLGARD® 184 - A clear silicone elastomer proposed as a conformal coating. This material provides a good reference point based on extensive experience by the photovoltaic industry in using this product.

DOW CORNING® X1-2561 Solventless Resin - A clear resin proposed for use as a conformal coating and as a cover material.

DOW CORNING® 96-083 Adhesive - A clear adhesive proposed for use in bonding cells to glass, wood and metal substrates.

DOW CORNING® Z-6082, Z-6030, Z-6020, 1204 Primer - Organofunctional silanes proposed as primers to provide adhesion of the coatings to substrates.

The materials of construction identified as candidates to provide mechanical support were:

Super Dorlux® - An outdoor weathering grade of hardboard from Masonite Corporation. Proposed for use as a substrate support material.

Solatex® - A clear, low iron containing glass from ASG Industries proposed a a superstrate support material.

Metals such as steel and aluminum were considered as substrate materials, however, no system could be envisioned which would be cost effective when the cost of the metal and cost of electrical isolation of the cellstring were combined.

The two encapsulation concepts assessed consisted of: a) a transparent superstrate with solar cells adhesively bonded with a thin glue line, coated with a white pigmented conformal coating and b) a solid substrate such as Super Dorlux® painted white with cells bonded to the surface and overcoated with a thin clear conformal coating.

Spectrolab supplied the cell circuits used in this evaluation which were two inch diameter 2-cell circuit-strings using silver ink screened metallization with solder-plated copper ribbon interconnectors.

Assessment of Encapsulation Concepts

The selection of stress tests and measurements was based on their relevance to outdoor weathering, temperature fluctuations and soil accumulation.

A. Ultraviolet Exposure

An Atlas Filtered Carbon-Arc Weather-Ometer®[23] was used to stress silicone materials with known weathering history. This instrument closely approximates the solar spectrum at a reasonable cost. We reviewed the commercially available light sources for stressing materials at wavelengths between 290-400 nanometers and found that a Xenon light source simulated the distribution of solar insolation better than any other source. However, the intensity of a Xenon lamp rapidly decays with time. This loss can be compensated by increasing the power to the lamp. Equipment is available from Atlas which monitors the light intensity from the Xenon lamp and adjusts the power to compensate for loss. This equipment is relatively expensive and the life of a Xenon lamp is short so the filtered carbon-arc light source was chosen as the most cost effective alternative for long term durability testing. In addition Dow Corning has used the Weather-Ometer® source for stressing silicone materials and found it a suitable method of accelerating the effects of sunlight on candidate materials. Dr. Roger Estey (JPL) measured the output of the Atlas Weather-Ometer® we are using to stress silicone mateials and found that the time average output of this source closely approximates the solar spectrum[24]. The intensity was in good agreement with that claimed by the manufacturer.

B. <u>Weather-Ometer® Stressing vs. Weathering History of Silicone and Modified Silicone Materials</u>

Based on the information from the technical review, ten materials with well defined periods of exposure and changes in properties were identified. Samples of these materials or products which closely duplicate them were exposed in an Atlas Sunshine Carbon Arc Weather-Ometer®. The resins were in the form of 2-4 mil coatings on metal panels and in one case as a coating on open weave fiberglass. The elastomers were exposed as 1/8" thick strips stretched to 20% greater than their unstressed length and in an unstressed condition.

The same properties that were monitored during outdoor weathering were tracked during artificial weathering. The mode of degradation as a function of time was monitored and correlation with natural weathering was made where possible.

Table I shows a comparison of the results obtained from samples exposed outdoors and those obtained using an Atlas Filtered Carbon Arc Weather-Ometer®.

None of the samples showed any appreciable effects from exposure in the Weather-Ometer® until 3,000 hours. Between 3,000 and 4,200 hours all of the resin coatings showed more signs of degradation than any of the coatings weathered naturally for up to 13 years.

Usually the resins degraded due to poor check ratings and loss of 60° gloss. Both of these signs of degradation are indicative of higher surface crosslinking and/or oxidation attributed to UV radiation.

Between 2,500 and 3,000 hours, large cracks became visible in DOW CORNING® 901 Resin exposed as a clear coating on an aluminum panel. A sample of DC® 901 exposed as a clear coating on woven glass cloth remained clear and transparent at 3,000 hours exposure. By 3,500 hours exposure, however, this sample became embrittled, lost adhesion to the glass substrate and most of the resin was missing from the glass cloth.

DOW CORNING® 808 Resin had no checking at 2,500 hours but between 2,500 hours and 3,000 hours dropped to a check rating of 7 indicating that the entire surface was covered with microcracks. The checking did not become any worse up to 4,200 hours exposure, however between 3,500 and 4,000 hours the 60° gloss dropped from 90% of the original value to 68% indicating additional loss in surface properties.

DOW CORNING® 996 Resin had the most significant change in checking between 2,500 and 3,000 hours of any of the resins tested. The check rating dropped from 10 (no checking) to 4 (visible cracks on 50% of the surface area). This resin also dropped from no loss of 60° gloss at 2,500 hours to 15% loss at 3,000 hours. By comparison after 10 years exposure in Midland, Michigan this resin had no loss of gloss and a check rating of 6.

The blend of 10% DOW CORNING® 840 - 90% 866 acrylic resin from Rohm and Haas also showed degradation due to checking between 2,500 and 3,000 hours when the check rating dropped from 10 to 6. No additional degradation was observed in either gloss or checking at 3,500 hours exposure. However, at 3,500 hours, 80% of the film was lost from the aluminum panel due to poor adhesion. In contrast, a sample of this resin blend had no loss of gloss or checking after 13 years exposure in Texas.

None of the elastomers show any visual signs of degradation after 4,200 hours exposure in the Weather-Ometer®. Samples of 132U silicone elastomer, which were removed from the Weather-Ometer® at periodic intervals through 3,786 hours, were measured for tensile strength and elongation. There is a relatively large variation in the values obtained but the data indicates a 10 to 20% loss in both tensile strength and elongation.

Test specimens of all the elastomers exposed in the Weather-Ometer® were removed after 5,000 hours exposure and tested. These included specimens exposed in both stressed and unstressed states.

None of the elastomers were visibly changed after this UV exposure; however, except for Silastic® 55 Silicone Rubber, all of the elastomers decreased in tensile strength and elongation. These results are shown in Table II. As might be expected, the samples which were exposed in a stretched condition had greater losses of tensile strength and elongation than samples in the relaxed state.

The losses in tensile strength caused by 5,000 hours of UV exposure for unstressed samples ranged from 6% for Silastic® LS-53 to 25% for Silastic® 132U. The percent elongation of DOW CORNING® RTV 3110 was within experimental error of the original value and the greatest loss in percent elongation, 36%, occurred with Silastic® 675. Samples which were stretched during exposure gave much different results. Stretched Silastic® LS-53, for example, had the greatest decrease in tensile strength, 49%, after exposure to UV.

Silastic® 55U gave anomolous results. The samples exposed to UV which were stretched 20% retained their tensile strength and elongation within experimental error. The unstressed samples on the other hand lost 63% of their original tensile strength. The stretched samples gave abnormally high values after exposure and the unstressed samples abnormally low values. The abnormally low values could be due to flaws in the test specimens although none were visible. There is no obvious explanation for the high tensile strength of the stressed samples.

This data indicates that although the silicone elastomers are inherently resistant to UV radiation compared with organic rubbers, the degree of this stability is dependent upon the formulation and nonsilicone components in the elastomer.

Clear silicone elastomers for which no previous weathering data was available were also exposed in the Filtered Atlas WeatherOmeter® and after 8,000 hours of exposure there were no visible changes in the elastomers. In addition, Q1-2577 Conformal Coating was exposed for over 7,500 hours as a coating over Super Dorlux®. The surface of the Q1-2577 was checked after this exposure but the coating still had good adhesion to the substrate and provided a continuous protective film.

C. Soiling Measurements

The soiling characteristic of the candidate encapsulation materials were assessed in two ways. The first was an accelerated test using carbon black and the second was the measurement of short circuit current of photovoltaic cells coated with the candidate materials as a function of outdoor exposure.

The first method provides a rapid assessment of the tackiness of a surface and its affinity for carbonaceous material. These results were superficial and did not correlate well with the more relevant results from outdoor exposure. The accelerated soiling results are shown in Table III but a lengthy description of the details is unwarranted because of the poor correlation with real outdoor soiling.

The outdoor soiling of candidate encapsulation materials was evaluated by adhesively bonding one cell circuits to the top of 3" x 9" x 1/8" soda lime float glass substrate panels with candidate silicone materials and then overcoating with these same materials. These samples were exposed on the roof of the Dow Corning Development Laboratory at its industrial site in Midland, Michigan at an angle of 45° south. This site is within 2 miles of 2 major industrial power plants. Although the pollution and soiling characteristics of this site has not been quantified, it can be subjectively rated as moderate i.e., causing more soiling than most remote sites but not as harsh as many urban sites.

Two samples of each candidate material was used in the outdoor soiling measurements. One was washed before the short circuit current and open circuit voltage of the encapsulated cell was measured and the other sample was measured in the unwashed condition. The measurements were made every two weeks. The assessment of the effects of washing was started four months after the original exposures, and therefore, the total accumulated exposure time is 110 days less than that obtained on the unwashed samples.

Measuring the I_{sc} of an encapsulated cell after outdoor exposure is the most relevant way to measure the effect of dirt pick-up. The wavelengths of solar radiation which power a silicon photovoltaic cell are predominantly outside the visual range so although visual inspection may indicate changes in cell performance due to dirt pick-up, this observation may not correlate with changes in module performance.

The design and construction elements of the one-cell circuits used to monitor soiling are shown in Figure 1.

The short circuit current (I_{sc}) and open circuit voltage (V_{oc}) of the test samples was monitored. The light source for measuring the cells, a 400 watt ELH lamp, is adjusted to 1,000 w/m^2 by adjusting its intensity using a standard reference solar cell from NASA Lewis Research Center. The light source is adjusted to give a I_{sc} of 140 milliamps and a V_{oc} of 478 milivolts at 28°C for the reference cell.

Random fluctuations in the short circuit current were observed during the portion of this work which were initially attributed to the effects of natural cleaning. These effects were undoubtedly present but the magnitude of these effects were discussed by an artifact of the measurement technique.

An analysis of this technique revealed that the fluctuations were probably due to slight variations in cell position during the measurement. The short circuit current measurements are obtained by illuminating the cells for a short period of time (approximately 2-3 seconds) using a 400 watt ELH lamp. It was observed that the cell position during this measurement was extremely critical. Differences in cell placement of 1-2 mm gave up to 10% variation in I_{sc} values. This sensitivity to cell position was overcome by moving the target area back from the light source several inches. An illumination of 1,000 watts/m^2 could still be obtained measured with a standard reference cell from NASA Lewis Research Center and the target area is twice as large as the cell's area. The cell position could be varied up to 1 cm with less than a 10% change in I_{sc}.

The results of these outdoor exposure tests are shown in Tables IV and V. Table V shows the results obtained with samples which were never washed. The most striking consequence of this exposure is the similarity in short circuit current (I_{sc}) values of all the cells which remained functional regardless of their composition and modulus of the resins used to coat them. The only exception was RTV 3140 which is a very low modulus elastomer. This elastomer was included as a reference sample and became very soiled. Its I_{sc} value was 358 mamps after 471 days exposure outdoors. All of the other samples had short circuit current values between 377 mamps and 391 mamps.

The cell encapsulated with DOW CORNING® X1-2561, an experimental solventless resin, failed due to an open circuit caused by the X1-2561 lifting the metallization from the cell surface. The coating of X1-2561 used in this outdoor exposure test was quite thick, approximately 40 mils, and its adhesion to the glass substrate was poor.

This experimental resin functions well as the cell adhesive for bonding cells to a glass superstrate. The glue line is clear, void free, and survives both humidity and thermal cycling stress.

The samples which were washed before making the I_{sc} measurements have much higher values than the unwashing samples at this time. However, if the I_{sc} values of the washed samples are compared with those of the unwashed samples at the same period of exposure 361 days (washed) of 388 days (unwashed) the values are extremely close. This data indicates that careful washing does not prevent loss of cell output due to soiling. The procedure used to wash the panels was to gently wipe the panels with a cheese cloth in a dilute Ivory Snow Soap solution and followed by a rinse with water.

At the conclusion of this contract, the outdoor exposure samples which are still intact will be sent to JPL to hopefully have this exposure study continued.

D. Temperature/Humidity Cycling

Test mini-modules were prepared for temperature/humidity cycling by adhering the photo-active side of the two-cell circuits to 3" x 9" x 1/8" panels of A.S.G. Industries' Solatex® Glass with the candidate silicone encapsulant. The back of the module was then coated with the same resin pigmented with TiO_2. This type of construction is referred to as a superstrate module because the structural element is the clear glass cover over the cells.

Substrate test modules were prepared by painting 3" x 9" x 1/8" panels of Masonite's Super Dorlux® hardboard with TiO_2 pigmented versions of the candidate encapsulants, laying the cells front side up on the coated substrate and the coating the cells and substrate with a clear version of the same resin. The stress conditions used are those specified by the Jet Propulsion Laboratory with all testing done at 90-95% relative humidity. The following temperature cycle was used: 1) room temperature to 40.5°C over a 2 hour period; 2) 16 hours at 40.5°C; 3) 40.5°C to room temperature over a 2 hour period; and then 4 hours at room temperature. The I_{sc} of each cell on each test module was measured separately.

All of these systems were cycled 75 times and there were no statistical decreases in short circuit current, see Tables VI and VII. Random fluctuations were observed which were due to an artifact of the measurement technique described earlier.

E. Exposure at High Humidity/High Temperature

The specimens using various encapsulation concepts from above after the temperature cycling stress from room temperature to 40.5°C at 95% relative humidity were stressed in the same humidity chamber at a constant 95% relative humidity and 70°C for 50 days. After this period, there was again no significant change in I_{sc}, see Tables VIII and IX. These results show that there were no chemical species present around the encapsulated cells which would cause serious corrosion in humid environments and that the encapsulants themselves were also free of chemical contaminants which would cause rapid corrosion in a wet environment.

In order for these high humidity stresses to differentiate between potential encapsulation concepts much higher stresses need to be used. All of the encapsulation concepts appear to provide adequate protection from moisture induced failure mechanisms. The additional criteria of UV stability and relief of stress during thermal cycling are more likely to discriminate between the encapsulation concepts.

F. Thermal Cycling Stress

Two-cell modules were prepared using both Super Dorlux® as a substrate and Solatex® Glass as a superstrate. Four silicone based materials were used as thin, protective conformal coatings with both structural members. These materials were; DOW CORNING® Q1-2577, DOW CORNING® 808 Resin, DOW CORNING® 840/Acryloid B48N Resin Blend, and DOW CORNING® X1-2561.

The candidate materials were used as both the adhesive and protective coating on the Super Dorlux®. The glass superstrate modules were all fabricated using X1-2561 as the clear, void-free adhesive.

These modules were thermally cycled from -40°C to +90°C using a schedule recommended by the Jet Propulsion Laboratory.

After four thermal cycles there were only four modules which did not have visible cracks. These were modules using DOW CORNING® Q1-2577 on both Super Dorlux® and Solatex® Glass and the module using DOW CORNING® 840/B48N on Super Dorlux® and the module using DOW CORNING® 808 resin on Solatex® Glass.

The two-cell modules which survived the first four thermal cycles were still intact after 40 cycles and the test was discontinued. The thermo-mechanical properties of Q1-2577 and DOW CORNING® 840 Resin were determined to obtain an understanding of why Q1-2577 exhibited superior stress relieving characteristics.

A good technique for measuring transitions in polymers as a function of temperature is with dynamic mechanical spectrometers. One of these instruments, a Torsional Braid Analyzer, was used by Professor John Gillham of Princeton to measure the dynamic modulus and damping factor of the two silicone polymers. The results of these analyses are shown in Figures 2 and 3. Figure 2 shows a sharp glass transition for Q1-2577 at -120°C which is well below the normal operating temperature range of photovoltaic modules. This transition accounts for the flexibility and ability of the cured silicone polymer to relieve stress during thermal expansion and contraction. In addition, there is a broad, poorly defined, transition centered at approximately 45°C. The absence of a sharp transition in the operating range and the relatively high modulus of Q1-2577 accounts for its resistance to cracking.

DOW CORNING® 840 Resin in contrast to Q1-2577 has a sharp glass transition in the normal operating range at 45°C. Rohm and Haas' Acryloid® B48N has a reported glass transition temperature of 50°C. These glass transitions in the operating range can account for the cracking and crazing which occurred using the blend of DOW CORNING® 840 with B48N.

Evaluation of Encapsulation Concepts

Mini-modules designed to conform to JPL's size requirements were prepared using Q1-2577 as the protective coating. These modules were fabricated at Spectrolab using 24 two inch cells on each module. Both Super Dorlux® substrate and glass superstrate style modules were made for testing and evaluation.

Six modules using Super Dorlux® as the substrate were made. Depressions were milled into the Super Dorlux® approximately as deep as the thickness of the solar cells. The cells were placed in these depressions making the surface of the solar cells even with the module surface which gave a flat smooth module. Five of these modules were given to JPL for environmental testing. Three glass modules were prepared using X1-2561 as the cell adhesive and Q1-2577 as the protective covering on the backside. These were also submitted to JPL.

The modules survived both the humidity stress test and the thermal cycling tests. The Super Dorlux® substrate modules became warped during the humidity cycling test but the encapsulant remained intact. These modules are still undergoing tests at JPL.

Silicone-Acrylic Cover Materials

A. Background

Low cost pottants are being evaluated as potential candidates for encapsulating and protecting photovoltaic cells. One promising candidate is ethylene vinyl acetate. This polymer has suitable physical and mechanical properties for this use but it is photo-oxidatively unstable. Therefore, ethylene vinyl acetate (EVA) must be protected from ultraviolet radiation in order for it to have a cost effective lifetime when used as an encapsulant for photovoltaic cells.

One method of providing this protection is to incorporate a UV absorber in a high modulus, dirt resistant, protective film used above the EVA pottant. This protective cover film must have the following properties:

1) Be dirt and scratch resistant.

2) Be durable and weatherable.

3) Have high transmissivity above UV wavelengths.

4) Contain a non-fugitive UV absorber.

5) Be available in useful form

6) Be cost effective

T. families of polymers with demonstrated weatherability which can be made suitable for this application are silicones and acrylates.

For example, polydimethylsiloxane, butyl acrylate and methylmethacrylate can be combined in various ratios to give copolymers with a wide range of physical and mechanical properties. These are the polymers used in this investigation.

Methylmethacrylate can be homopolymerized to a hard, weatherable plastic. Plexiglas® is a familiar trade name for this polymer.

Butylacrylate and polydimethylsiloxane can both be used to plasticize polymethylmethacrylate and such copolymers are lower modulus and have higher elongation than polymethylmethacrylate.

Two approaches were used in an attempt to obtain silicone-acrylate copolymers. The first approach was to graft silanol functional fluids on prepolymerized acrylate resins. This approach was not successful principally because of the incompatibility of the silicone fluid and acrylate polymer. Even at high dilution in a co-solvent, the two polymers separated into different layers.

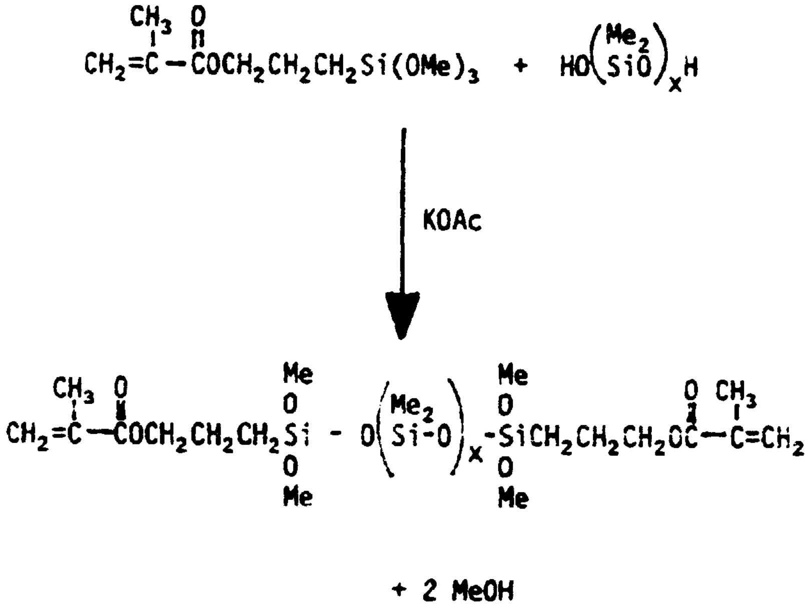
A two-step process was used in the second approach and although this approach was more complicated from the viewpoint of chemical processing, it was successful.

A silicone-acrylate copolymer was prepared by first reacting an acrylate functional silane with a polydimethylsiloxane fluid and then copolymerizing this acrylate functional fluid with butyl acrylate and methylmethacrylate monomers.

Additionally this technique provided a propitious method of chemically incorporating the UV absorber into the copolymer. Permasorb MA is a commercially available, acrylate functional, orthohydroxybenzophenone which can be coreacted with acrylate monomers.

B. Results and Discussion

Methacryloxypropyltrimethoxysilane, DOW CORNING® Z-6030, was coreacted with a silanol functional polydimethylsiloxane fluid, DOW CORNING® Q1-3563. An excess of Z-6030 was used to promote endcapping of the polydimethylsiloxane chains rather than coupling. Potassium acetate was used to accelerate the reaction.



The excess Z-6030 and methanol were removed by heating in vacuum and the potassium acetate removed by filtration.

The resulting liquid could be cured to a soft gel using azobisisobutyronitrile (Vazo), a free radical catalyst.

This acrylate functional fluid was coreacted with butyl acrylate and methylmethacrylate using the following ratio of ingredients:

Acrylate Functional Fluid	20
Butyl Acrylate	40
Methylmethacrylate	40
Permasorb MA	1.0
DOW CORNING® Z-6062 (chain regulator)	0.35
Vazo (catalyst)	0.5
Toluene (Solvent)	200

The monomers, chain regulator, and catalyst were all combined and slowly added to toluene which was preheated to 100°C. This method of combining reactants is not advised for repeated or large scale polymerizations because of the potential for premature and uncontrolled reaction. The same polymer can be prepared by dissolving the catalyst in solvent and adding it separately to the hot toluene simultaneously with the other ingredients.

The polymer which was prepared was sprayed on decal paper to form a thin film, approximately one mil thick. A thicker film was obtained by pouring the solution of polymer on a flat surface and allowing the solvent to evaporate.

Cellulose acetate samples were protected with a thin film of the polymer and exposed in a Filtered Atlas Weather-Ometer®. These samples were unchanged after 1,000 hours exposure. Unprotected cellulose acetate becomes cracked and crazed after 48 hours exposure.

Samples of cured polymer film containing 0.25% Permasorb MA were extracted with water and compared with extracts of samples having the same composition but with Permasorb MA added as a physical blend and not copolymerized. Extracts of the samples with Permasorb MA added as a physical blend had much more UV absorption than extracts of the copolymerized Permasorb MA films, see Figure 4.

The rate of homopolymerization of Permasorb MA is much lower (approximately 50 times slower) than homopolymerization of methylmethacrylate[25]. The degree of copolymerization versus oligimerization of Permasorb MA in this system has not been established.

Much work is needed to optimize the formulation and process conditions to develop the most cost effective practical polymers for this application.

The concept of using this approach to protect UV sensitive polymers has been successfully demonstrated and was the goal of this work.

This technology has been transferred to Springborn Laboratories for further development.

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TABLE I

OUTDOOR VS. ATLAS SUNSHINE CARBON ARC WEATHER-OMETER® (WOM) STRESSING: EFFECTS ON PROPERTIES

RESIN OR ELASTOMER	FORM OF SAMPLE	SITE & DURATION OF EXPOSURE	CONDITION OF SAMPLE
1. DOW CORNING® 808 Resin	3-4 mil coating on aluminum panels	6 years Florida, 45° south	36% loss 60° gloss, no checking or dirt retention.
		5,256 hours filtered WOM	0 check rating, 50% loss 60° gloss.
2. DOW CORNING® 901 Resin	6 mil coating on fine weave fiberglass	7 years Arizona, 45° south	99% of original 350-2400 NM transmission
		4M Langleys - Emmaqua	94% of original 350-2400 NM transmission
		3,524 hours filtered WOM	Resin flaked off of substrate.
3. B66 Acrylic/ DC® 840 Blend	3-4 mil coating on aluminum and steel panels	13 years Texas	Slight dirt retention, no loss gloss or checking.
		7 years Florida, 45° south	High corrosion protection.
		3,750 hours Filtered WOM	100% coating off. No measurement.
4. DOW CORNING®	2 mil coating on aluminum	10 years Midland	No loss gloss, no color change, checking rating 6.
		4,981 hours filtered WOM	69% loss 20° gloss (spots from water spray), 37% loss of 60° gloss, checking 0, no dirt retention.
5. LS 53 Rubber	1/8" thick strips-folded, stretched 20%, unstressed.	20 years Florida	Slight dirt & mildew, no cracking or checking.
		5,256 hours filtered WOM*	No change.

*Removed and tested for tensile strength and elongation, see Table II

TABLE 1 - Continued

RESIN OR ELASTOMER	FORM OF SAMPLE	SITE & DURATION OF EXPOSURE	CONDITION OF SAMPLE
6. RTV 132U Elastomer	1/8" thick strips-folded, stretched 20%, unstressed	20 years Florida	Some loss of tensile and elongation, same as LS 53.
		5,256 hours filtered WOM*	Slight trace dirt.
7. RTV 501 (3110 RTV) Elastomer	1/8" thick strips-folded stretched 20%, unstressed	16 years Florida	Slight dirt retention and mildew.
		5,041 hours filtered WOM*	No checking
8. 55U Silastic® Rubber	1/8" thick strips-folded, stretched 20%, unstressed	19 years Florida	Slight dirt retention and mildew
		5256 hours filtered WOM*	No change
9. Silastic® 675 Rubber	1/8" thick strips-folded, stretched 20%, unstressed	19 years Florida	Slight decrease in durometer, tensile, and elongation, some surface cracking.
		5,256 hours filtered WOM*	No change.
10. RTV 781	6 mil coating on aluminum	20 years Wisconsin	Dirt pickup, slight lowering in durometer
Building Sealant	6 mil coating on aluminum	5,629 hours filtered WOM	Some loss 20° gloss, 10% blisters.

*Removed and tested for tensile strength and elongation, see Table II

TABLE II

Elastomers	Hours WOM	# of Specimens	PSI Tensile	% Change	Elong- ation	% Change
Silastic® LS-53 Control	0	1	1026		550%	
Weathered Flat	5256	2	968	-5.6%	450%	-18%
Weathered 20% Stretched	5256	1	519	-49%	275%	-50%
SILASTIC® 675 Control	0	2	529		275%	
Weathered Flat	5256	2	396	-25%	175%	-36%
Weathered 20% Stretched	5256	2	292	-45%	100%	-64%
Silastic® 132U Control	0	2	426		305%	
Weathered Flat	5256	2	320	-25%	212%	-30%
Weathered 20% Stretched	5256	2	276	-35%	238%	-22%
Silastic® 55U Control	0	2	1120		825%	
Weathered Flat	5256	2	420	-62%	340%	-59%
Weathered 20% Stretched	5256	2	1118	-0.2%	875%	+6%
DOW CORNING® 3110 RTV Control	0	2	285		220%	
Weathered Flat	5543	3	250	-12%	197%	-10%

TABLE III

CANDIDATE SILICONE ENCAPSULATION MATERIALS

SILICONE OR MODIFIED SILICONE	USE	$/lb. SOLIDS (1978 $)	$/ft²/Mil.	INITIAL TANGENTIAL MODULUS(psi)	ACCELERATED DIRT PICK-UP	PHENYL/ METHYL UP
A. DC® 840/B48N Resin Blend	1. Conformal Coating 2. UV Containing Top Cover 3. Pigmented Bottom Cover	4.32/1.51	.012	43,500	9.5-10	High
B. DC® 808 Resin	Same as A	5.08	.026	27,500	5	Low
C. Q1-2577 Conformal Coating	Same as A	9.33	.052	2,450	5	Low
D. RTV 3140	As a pottant	11.19	.06	--	0-1	Negligible
PRIMERS						
A. Z-6082 Silane		4.30	.005/5μ	--	--	--
B. Z-6030 Silane		8.65	.01/5μ	--	--	--
C. Z-6020 Silane		6.35	.0075/5μ	--	--	--
D. DC® 1204 Primer		5.40	.004/5μ	--	--	--
E. DC® 3-6060 Primer		NA	--	--	--	--
ADHESIVES						
A. X1-2561*		10.00	.06	--	9	Medium
B. RTV 3140		11.19	.06	--	--	Low

*The cost of this experimental product is based on estimates assuming large scale production and use.

TABLE IV

V_{oc} in millivolts

I_{sc} in milliamps

V_{oc} and I_{sc} versus Outdoor Exposure (Washed before measurement)

Days Exposure	DC-184 Voc	DC-184 Isc	Q1-2577 Voc	Q1-2577 Isc	DC-840/848N Voc	DC-840/848N Isc	RTV 3140 Voc	RTV 3140 Isc	X1-2561 Voc	X1-2561 Isc	Days Exposure	DC-808 Voc	DC-808 Isc
0	589	478	588	527	587	399	592	480	594	431	0	508	509
16	579	569	578	498	578	388	582	438	583	411	13	579	487
26	577	493	476	545	578	396	580	460	584	425	25	582	482
42	579	477	577	516	576	387	581	461	584	416	37	578	447
55	577	460	573	486	578	382	580	580	451	586	51	582	498
67	582	484	574	469	575	366	576	371	576	334	66	582	486
78	578	389	577	511	577	424	576	400	580	391	93	581	475
92	581	472	578	492	577	395	582	437	585	402	107	577	457
107	577	473	577	497	585	445	582	427	588	445	128	584	483
134	582	468	578	492	585	440	580	413	588	436	142	586	484
148	576	436	574	473	580	442	577	406	585	423	157	587	475
169	585	480	581	474	589	464	583	394	594	445	172	589	454
183	586	477	582	497	590	458	586	416	594	454	191	583	473
198	587	466	587	494	591	456	587	406	594	440	203	585	472
213	588	480	585	505	591	462	587	410	597	437	224	581	470

TABLE IV - continued

V_{oc} and I_{sc} versus Outdoor Exposure (Washed before measurement)

Days	DC-184		Q1-2577		DC-840/B48N		RTV 3140		X1-2561		Days	DC-808	
Exposure	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Exposure	Voc	Isc
232	583	470	581	498	588	450	583	413	594	447	238	584	461
243	583	465	581	489	585	440	584	412	593	445	252	586	472
264	483	439	582	495	588	453	583	413	594	458	269	589	463
278	583	475	581	501	588	462	584	413	593	456	287	587	441
292	586	468	580	493	590	454	583	398	595	447	300	585	445
309	568	457	587	473	573	452	589	401	579	452	321	584	440
327	583	448	585	469	583	371	590	430	596	430			
340	282	458	582	483	582	387	589	457	594	445			
361	583	443	581	460	587	439	580	375	583	440			

TABLE V

V_{oc} in millivolts

I_{sc} in milliamps

V_{oc} and I_{sc} Versus Outdoor Exposure (Unwashed)

Days Exposure	DC-184 Voc	DC-184 Isc	Q1-2577 Voc	Q1-2577 Isc	DC-840/B48N Voc	DC-840/B48N Isc	RTV 3140 Voc	RTV 3140 Isc	X1-2561 Voc	X1-2561 Isc	Days Exposure	DC-808 Voc	DC-808 Isc
0	577	489	583	469	572	473	573	487	549	458	0	577	505
11	569	474	570	451	557	474	559	471	559	478	7	561	432
26	576	448	580	441	568	453	569	430	560	412	22	567	426
37	584	463	589	450	576	439	578	547	570	396	33	570	383
44	581	465	588	452	576	450	577	452	571	396	40	576	416
53	590	469	596	434	581	416	587	449	579	378	49	581	413
60	584	515	590	494	574	445	577	438	570	406	56	576	424
66	576	500	587	484	569	441	574	464	568	349	62	572	425
81	585	425	590	423	576	342	580	403	567	315	77	577	392
96	588	451	598	445	582	413	586	423	574	369	92	582	396
108	584	458	590	429	575	413	578	357	575	364	104	577	430
124	581	359	590	388	579	419	579	420	571	330	120	577	397
134	582	469	589	461	576	434	576	417	569	356	130	574	410
150	587	468	593	460	560	413	580	409	569	329	146	576	488
163	582	428	591	434	578	436	578	408	570	308	159	576	396
175	587	451	590	379	582	424	583	421	580	111	171	580	420
187	587	467	593	438	579	430	579	410	-0-		183	572	385
201	583	439	587	397	576	398	576	376	-0-		197	573	406

TABLE V - Continued

V_{oc} in millivolts

I_{sc} in milliamps

V_{oc} and I_{sc} Versus Outdoor Exposure (Unwashed)

Days Exposure	DC-184 Voc	DC-184 Isc	Q1-2577 Voc	Q1-2577 Isc	DC-840/B48N Voc	DC-840/B48N Isc	RTV 3140 Voc	RTV 3140 Isc	X1-2561 Voc Isc	Days Exposure	DC-808 Voc	DC-808 Isc
216	585	441	590	435	577	458	581	417	-0-	212	580	426
243	586	433	590	429	583	445	580	405	-0-	239	582	434
257	581	394	588	427	578	444	576	407	-0-	253	577	404
278	586	440	595	436	585	449	583	402	-0-	274	583	439
292	586	428	592	422	585	441	582	392	-0-	288	584	437
307	581	325	597	415	588	436	586	390	-0-	303	589	430
322	591	401	598	396	589	406	586	380	-0-	318	589	441
341	582	356	592	418	585	381	582	366	-0-	337	584	433
353	585	406	591	408	583	435	579	393	-0-	349	584	431
388	587	420	590	409	585	434	579	376	-0-	384	583	424
402	585	416	594	408	583	439	581	378	-0-	398	584	430
419	572	405	577	405	577	438	566	375	-0-	415	569	432
437	585	398	595	397	585	419	582	362	-0-	433	585	404
450	588	411	594	406	586	429	582	366	-0-	446	584	429
471	584	391	591	377	581	388	577	358	-0-	467	581	379

TABLE VI

SUPER DORLUX SUBSTRATE MODULE DESIGN
TEMPERATURE CYCLING TEST

AT 95% RELATIVE HUMIDITY
ROOM TEMPERATURE TO 40.5°C

	Q1-2577				X1-2561				DC-840/B-48N				DC-808				RTV-3140			
	CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2	
CYCLES	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc
0	551	376	573	460	561	399	569	403	586	408	575	472	574	339	576	380	567	472	570	430
5	580	378	596	492	581	515	588	506	590	401	581	470	595	470	584	382	0	0	574	453
15	567	378	595	492	567	393	574	415	592	401	577	436	582	315	591	380	-	-	587	517
25	573	370	591	478	567	391	571	393	586	303	577	459	587	341	577	353	-	-	577	427
34	568	316	589	427	567	381	572	381	588	335	571	292	575	236	575	270	-	-	575	333
44	573	389	590	515	577	550	570	427	589	340	574	488	571	351	569	395	-	-	574	474
54	577	392	593	495	571	405	574	428	591	424	576	485	580	344	579	389	-	-	581	464
65	576	386	593	501	568	388	573	281	589	424	579	501	579	354	578	369	-	-	579	474
75	572	327	586	355	567	344	572	368	590	427	565	403	576	360	573	389	-	-	574	454

225C

TABLE VII

GLASS SUPERSTRATE MODULE DESIGN
TEMPERATURE CYCLING TEST

AT 95% RELATIVE HUMIDITY
ROOM TEMPERATURE TO 40.5°C

	QI-2577				X1-2561				DC-840/B-48N				DC-808				RTV-3140			
	CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2		CELL 1		CELL 2	
CYCLES	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc	Voc	Isc
0	582	423	575	386	589	474	580	504	584	466	585	394	590	466	590	472	579	438	584	463
5	587	421	592	484	596	460	584	489	588	427	585	377	595	406	591	459	586	430	591	459
15	584	428	587	499	593	473	580	501	586	440	582	381	592	416	588	426	584	443	588	470
25	580	401	586	445	590	450	579	491	579	401	581	365	587	383	589	423	582	453	586	441
34	578	413	582	475	582	411	575	455	580	411	580	379	588	411	585	429	580	433	584	460
44	580	332	568	264	588	454	575	479	578	420	579	389	587	427	584	450	580	451	583	501
54	584	441	575	367	577	314	577	460	585	368	582	381	592	380	571	270	583	446	573	347
65	583	432	573	367	575	302	579	500	582	444	581	384	589	419	571	285	582	448	572	352
75	573	405	565	374	580	373	573	384	576	350	576	330	584	335	586	341	577	417	567	336

TABLE VIII

SUPER DORLUX SUBSTRATE MODULE DESIGN

STRESSED AT 95% RELATIVE HUMIDITY/70°C

Constant - 70°C/95%

Days Exposure	Q1-2577				X1-2561				DC-840/B48N				DC 808				3140/3110			
	A Cell		B Cell		A Cell		B Cell		A Cell		B Cell		A Cell		B Cell		A Cell		B Cell	
	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}
0	572	327	586	355	567	344	572	368	590	427	565	403	576	360	573	389	- 0 -		574	454
2	577	395	592	485	572	444	578	452	590	438	577	483	581	397	584	428	-	-	581	488
4	582	438	597	532	578	480	583	505	590	415	573	456	582	398	582	445	-	-	583	523
8	580	433	594	516	578	477	580	479	591	437	577	502	584	421	581	422	-	-	586	423
17	578	391	590	455	577	451	581	441	588	380	571	398	581	398	582	386	-	-	580	476
24	580	415	588	422	579	438	576	396	587	396	573	460	575	350	581	426	-	-	580	471
32	578	386	593	492	573	386	579	437	589	426	575	463	577	335	580	381	-	-	579	448
50	582	440	594	474	578	495	584	401	587	458	576	462	577	406	580	423	-	-	576	417
71	587	429	597	449	586	493	Lead Broke		588	408	578	428	580	377	583	399	-	-	577	358

*Dorlux Substrate
V_{oc} - millivolts/I_{sc} - milliamps

2250

TABLE IX

GLASS SUBSTRATE MODULE DESIGN

STRESSED AT 95% RELATIVE HUMIDITY/70°C

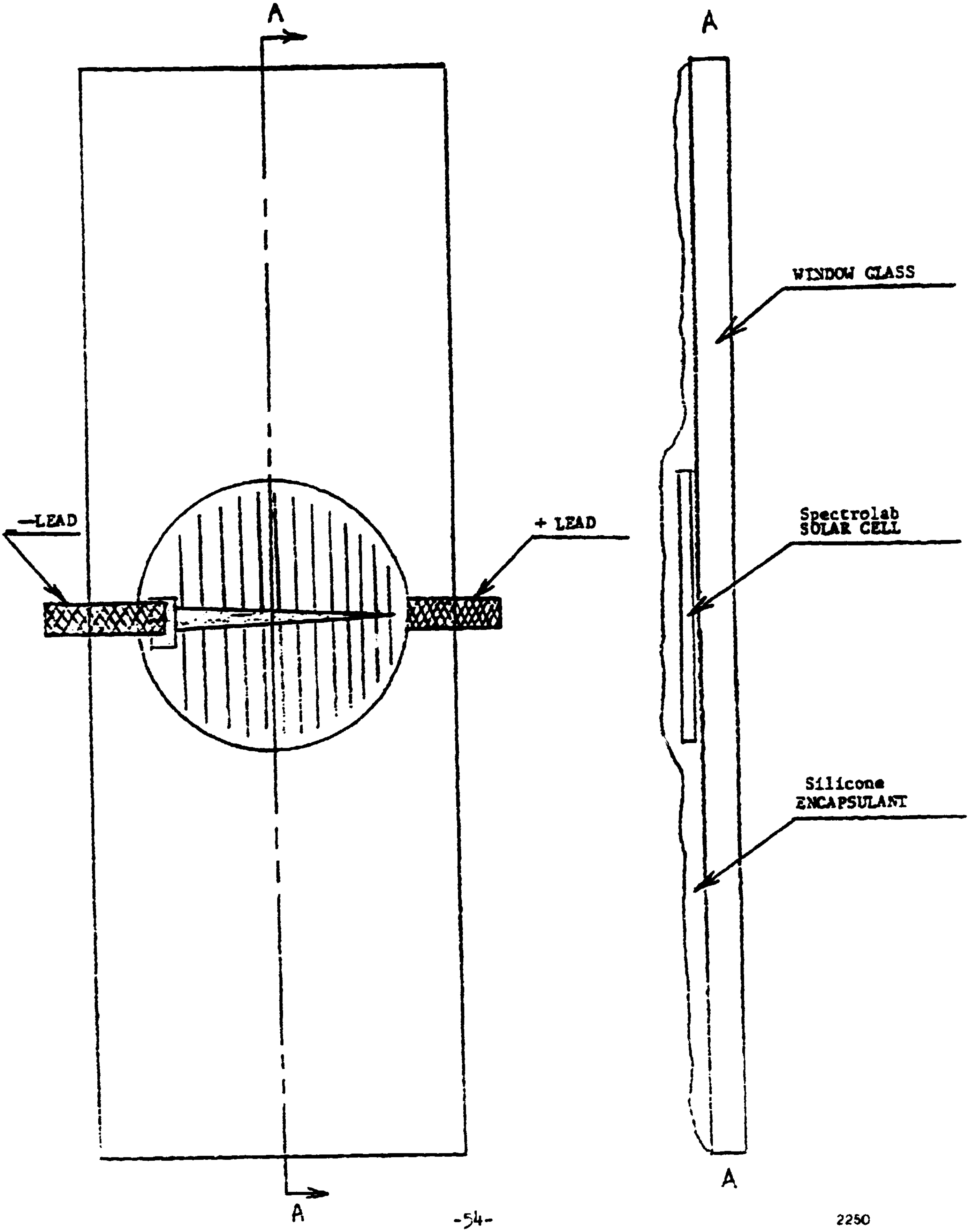
Constant - 70°C/95%

Days Exposure	Q1-2577				X1-2561				DC-840/B48N				DC 808				3140/3110			
	A Cell		B Cell		A Cell		B Cell		A Cell		B Cell		A Cell		B Cell		A Cell		B Cell	
	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}	V_{oc}	I_{sc}
0	573	405	565	374	580	373	573	384	576	350	576	330	584	335	586	341	577	417	567	336
2	583	433	577	392	591	470	577	450	584	464	577	332	590	413	585	413	584	440	584	434
4	578	401	579	423	592	523	575	449	583	484	584	423	591	437	587	417	584	484	579	414
8	585	461	582	439	590	468	575	426	583	453	583	396	593	448	585	437	580	436	578	391
17	581	426	578	419	593	465	577	471	583	459	584	405	588	394	578	371	581	452	585	469
24	582	427	580	428	590	468	568	338	581	407	584	345	591	401	579	391	582	434	587	458
32	574	376	581	449	591	469	575	413	583	442	583	386	589	388	581	403	583	457	576	374
50	576	401	577	397	579	430	576	392	575	343	580	360	584	406	579	405	578	462	583	451
71	582	354	580	349	587	410	583	433	583	372	587	293	590	383	584	379	585	435	580	444

*Glass Superstrate
V_{oc} - millivolts/I_{sc} - milliamps

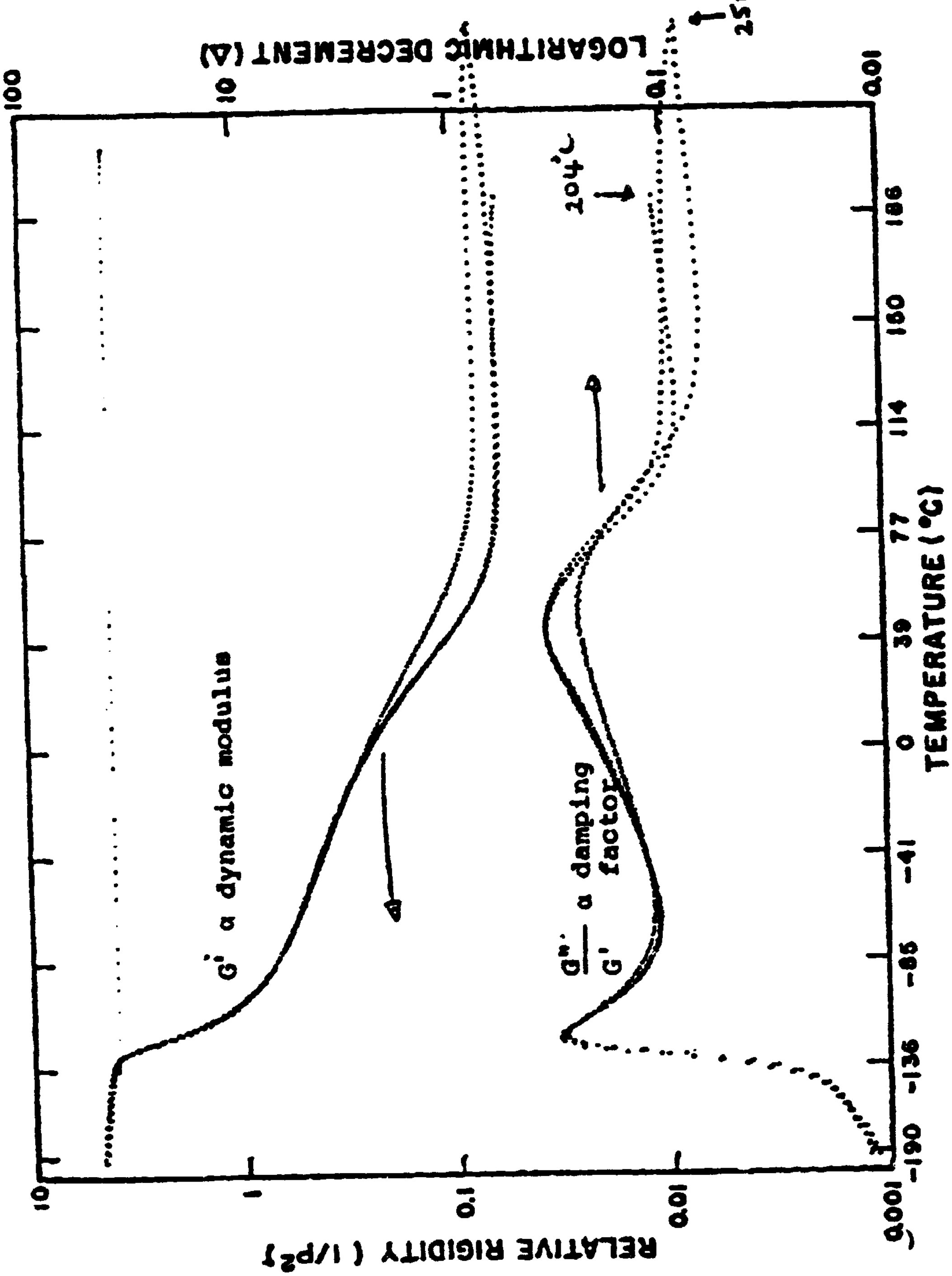
2250

FIGURE 1



2250

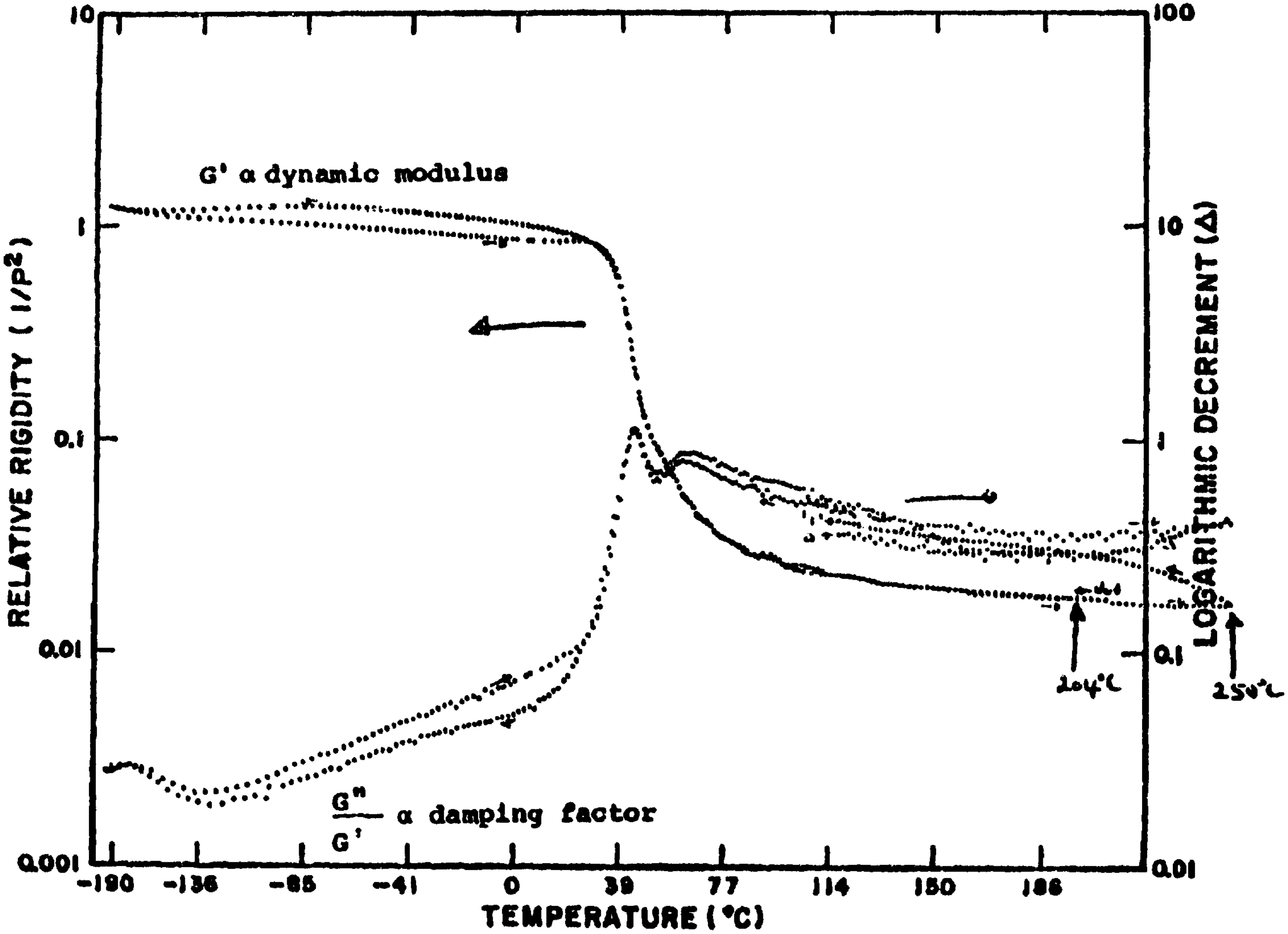
FIGURE 2



Q1-2577

PLTr 2 ∧ 2

FIGURE 3



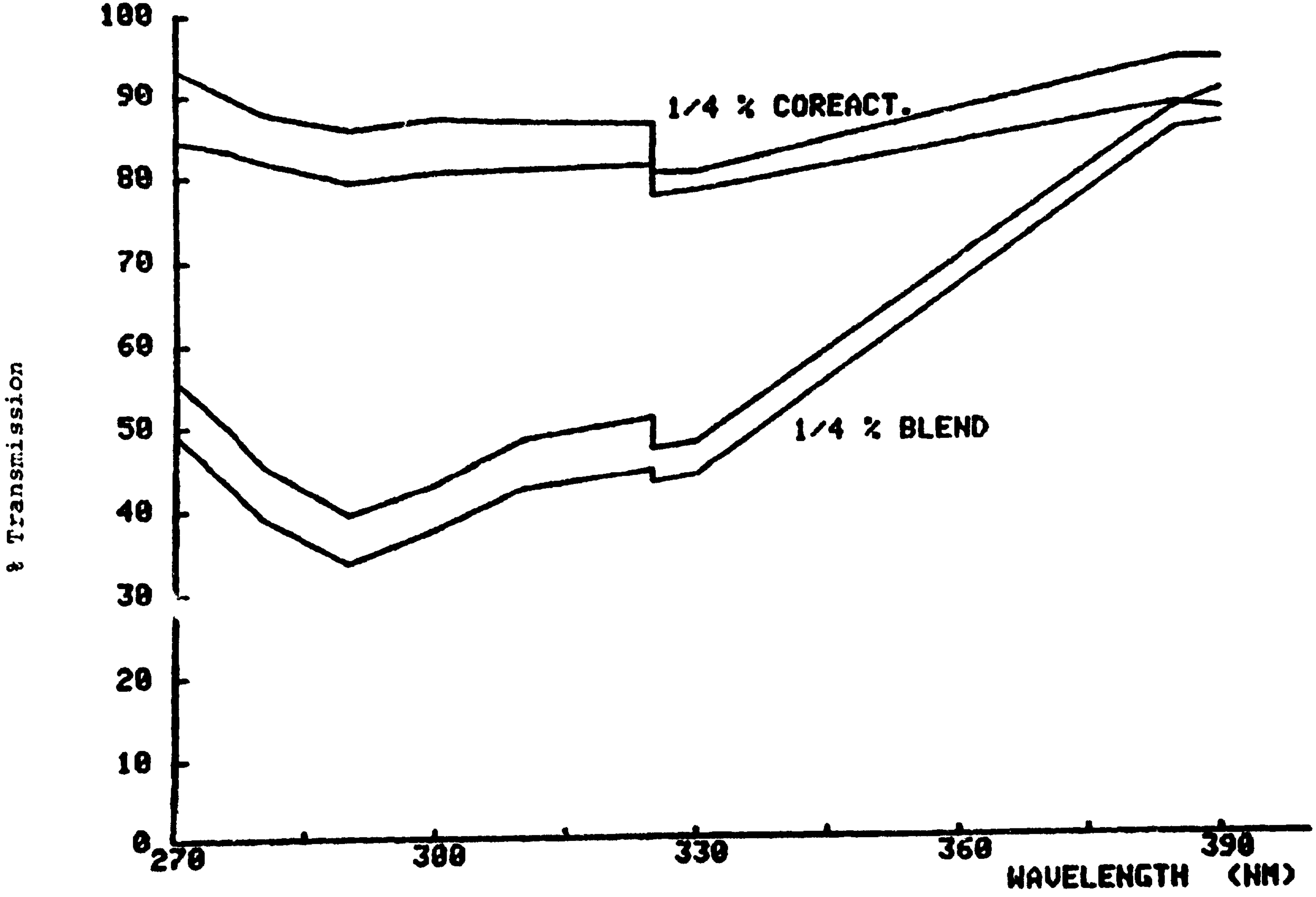
DC-840 PIN 293
PIN: 204°C → −195°C → 250°C → 115°C
1.5°C/min

2250

FIGURE 4

UV EXTRACTION STUDY

OF FILMS CONTAINING PERMASORB MA



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